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DEMODULATION OF WIDE-BAND FREQUENCY MODULATION BY A PHASE-LOCK TECHNIQUE

by Richard C. Booton, Jr.

*Space Technology Laboratories, Inc.
Redondo Beach, California*



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SUMMARY

The wide-band phase-lock demodulator described herein was developed by the Space Technology Laboratories, Inc. for Goddard Space Flight Center. The design objective was a demodulator capable of handling frequency-modulated television signals. Base-band signals were to be standard 525 line video, with a bandwidth of approximately 3 Mc, plus an aural subcarrier at 4.5 Mc. Mathematical and physical descriptions of the demodulator, together with theoretical and experimental TV data, are presented. The principal design problem overcome during the development was the decrease of the loop time delay sufficiently to achieve a loop bandwidth of approximately 7.5 Mc without stability problems. Monitor pictures are used to compare the performance of the phase-lock demodulator with a conventional discriminator.

CONTENTS

Summary	i
INTRODUCTION	1
MATHEMATICAL DESCRIPTION	2
PHYSICAL DESCRIPTION	3
EXPERIMENTAL MEASUREMENTS	
WITH SINUSOIDAL BASE-BAND SIGNAL	7
EXPERIMENTAL TV DATA	7
CONCLUSIONS	12
ACKNOWLEDGMENTS	12

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INTRODUCTION

With the recent launching of the first Telstar satellite, the first experimental demonstration of telephone and television communication by means of an active satellite repeater system was achieved. The first spacecraft for this purpose was of necessity limited in transmitter power capability. Now, and for some time, the communication system design must center around achieving maximum information flow per watt of satellite radiated power, even at the expense of another precious quantity — bandwidth.

The modulation technique chosen for the early satellite relays has been wide-band analog frequency, or phase, modulation. This encoding has the capability of yielding high output signal-to-noise ratio with small spacecraft transmitted power. However, full advantage cannot be taken of the power reduction capability of this modulation form with a standard-discriminator demodulator. Accordingly, considerable effort has been devoted to the development of more efficient demodulation schemes. Two examples are the Bell Telephone Laboratories FM-feedback demodulator and the phase-lock demodulator to be described in the present paper.

The phase-lock demodulator was developed by the Space Technology Laboratories, Inc. for Goddard Space Flight Center. The design objective was a demodulator capable of handling frequency-modulated television signals. Base-band signals were to be standard 525 line video, with a bandwidth of approximately 3 Mc, plus an aural subcarrier at 4.5 Mc. A demodulator capable of handling such a TV signal can handle between 120 and 240 frequency-division-multiplex telephone channels.

Evaluation of several methods that reduce the required signal, including the FM-feedback discriminator, led to the selection of the phase-lock technique. The use of phase-lock circuits has yielded extensive experience in different applications. Much of the STL experience was obtained in

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†Director, Communication Laboratory, Space Technology Laboratories, Inc., Redondo Beach, California.

connection with the design of receivers for satellites and deep space; such applications usually require extremely sensitive receivers with very narrow bandwidths. Although wide-band demodulation was different, the phase-lock technique was sufficiently promising to use for the development of a wide-band demodulator. The prime advantage of the phase-lock technique is the extreme simplicity of the circuits, which makes possible low loop time delays and, accordingly, high loop bandwidths.

MATHEMATICAL DESCRIPTION

Figure 1 shows an abbreviated block diagram of the wide-band phase-lock demodulator developed to handle TV signals. The phase-lock loop itself is shown to the left of the figure and consists of three units: a voltage controlled oscillator (VCO) that generates a replica of the signal input, a phase detector to measure the phase relation between the signal input and the VCO output, and a third unit for amplification and filtering to control the loop characteristics. Because of the feedback action the phase of the VCO output follows the phase of the signal input, at least within the dynamic capability of the loop.

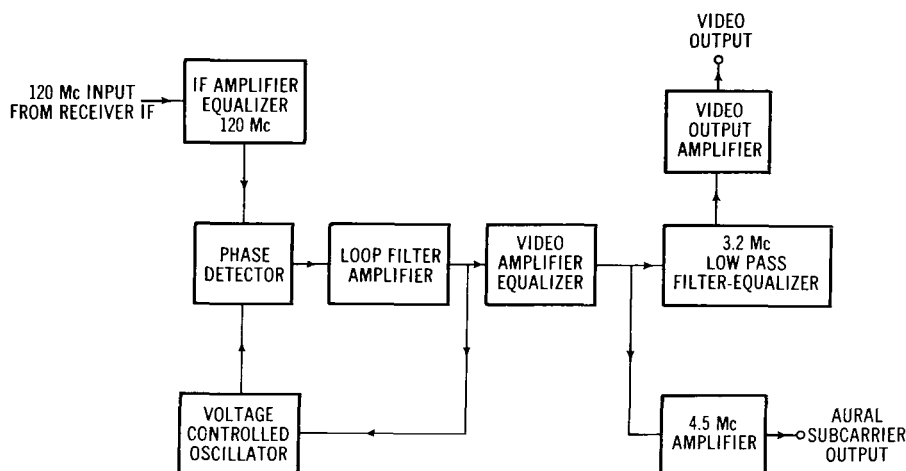


Figure 1—Wide-band phase-lock demodulator for TV

The dynamic characteristics selected for the loop were of the second order, although higher order loops have been investigated. Figure 2 gives a mathematical description of a linearized second order loop. The difference between the input phase and the VCO output phase is determined by a phase detector, whose action is indicated as a simple phase subtraction because the nonlinear effects of the actual phase detector have been neglected. The loop filter is shown as a linear block that furnishes gain and a simple compensation to insure a satisfactory closed-loop characteristic. The principal effect of the VCO is indicated as an integration from the voltage input to the phase of the VCO output. In addition to the usual second order parameters, pure time delays are shown both in the forward path and in the

feedback path. Although these delays are shown as pure time delays, they might in fact be a convenient approximation to higher order effects whose characteristic frequencies are so high that the dominant effect over the loop bandwidth is simply a phase shift that is linear with frequency. The two equations in Figure 2 show the mathematical form for the transfer function from the phase input to the VCO output, and the transfer function from the phase input to the phase error.

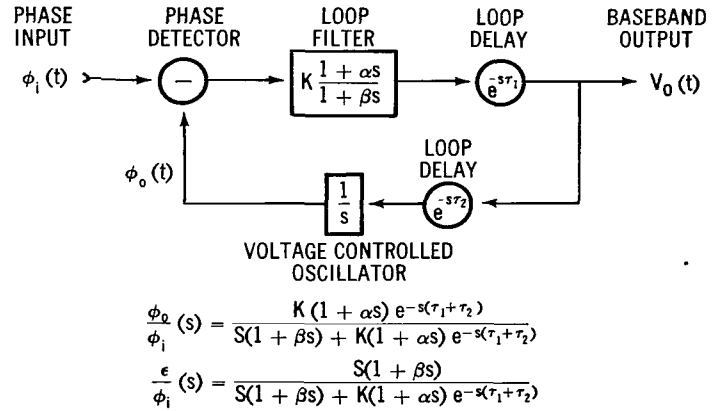


Figure 2—Linearized second order phase-lock loop

If it were possible to eliminate the time delays, achievement of any value of loop bandwidth would be a simple matter of selecting appropriate values for the constant K , α , and β . The presence of the time delays τ_1 and τ_2 , however, restricts the bandwidths that can be achieved satisfactorily. Figure 3 is a Nyquist diagram for a circuit such as that shown in Figure 2, and indicates the tendency of the time delays to cause system instability. For a fixed total time delay, attempting to increase the gain K beyond a certain value results in an unstable system. Analysis indicated that, in order to achieve the desired loop bandwidth of approximately 7.5 Mc, the total time delay had to be reduced to approximately 30 nanoseconds.

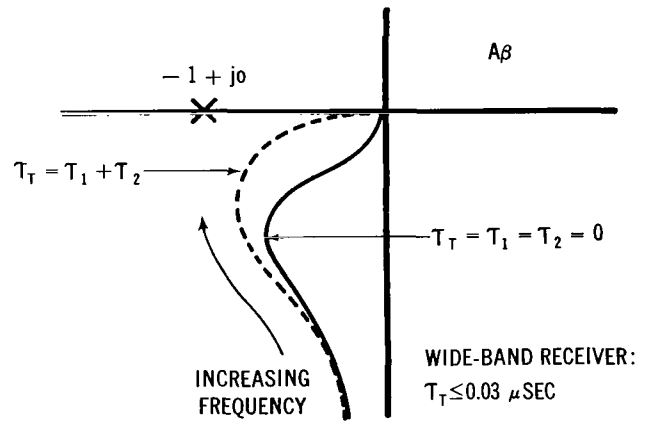


Figure 3—Nyquist diagram; stability criteria

PHYSICAL DESCRIPTION

First, it should be noted that an appreciable amount of conventional receiving equipment is required in addition to the demodulator. Figure 4 is the block diagram of a complete receiving system. The output of the antenna-mounted preamplifier, mixer, and IF amplifier is the input to the rack-mounted portion of the receiver. The rack-mounted equipment includes the demodulator, amplifiers, filters, and equalizers. A standard FM discriminator is also provided. A decision was made to mount all this equipment on one chassis; Figure 5 shows an artist's conception of how the receiver would appear physically. Note that the phase demodulator itself consists of only two modules. Figure 6 is a photograph of the actual receiver as completed. Figures 7 and 8 respectively show the physical appearance of the phase detector and filter, and the VCO. As an illustration of the other modules, Figure 9 is a photograph of an IF amplifier.

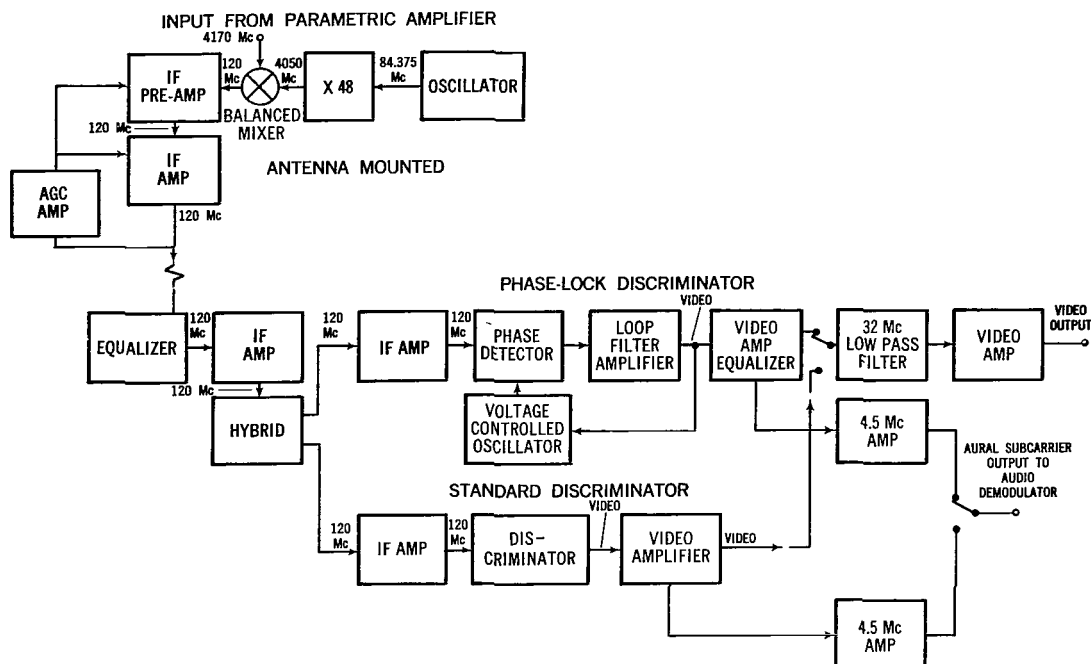


Figure 4—Relay wide-band phase-block receiver, block diagram

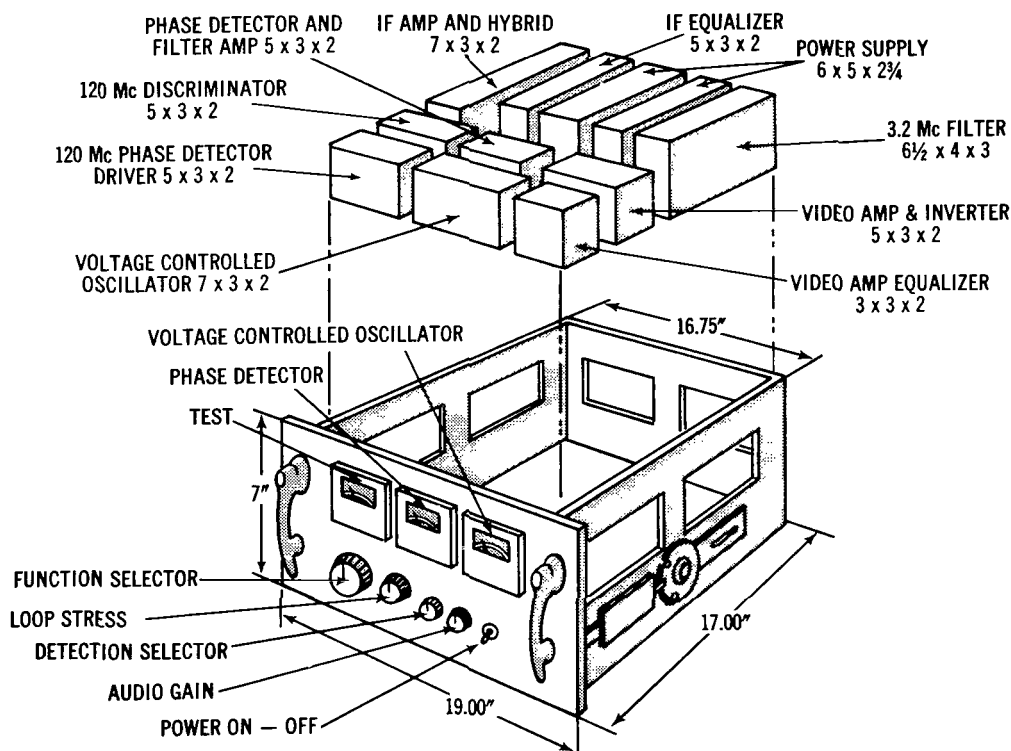


Figure 5—Artist's conception of complete receiver

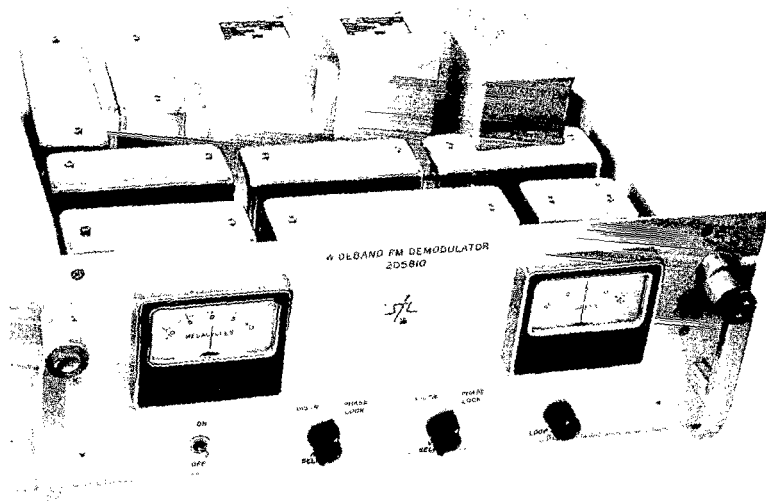


Figure 6--Actual receiver

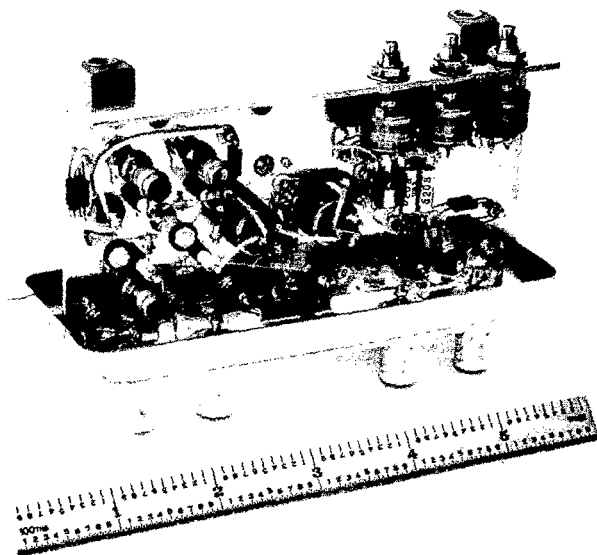


Figure 7--Phase detector and filter

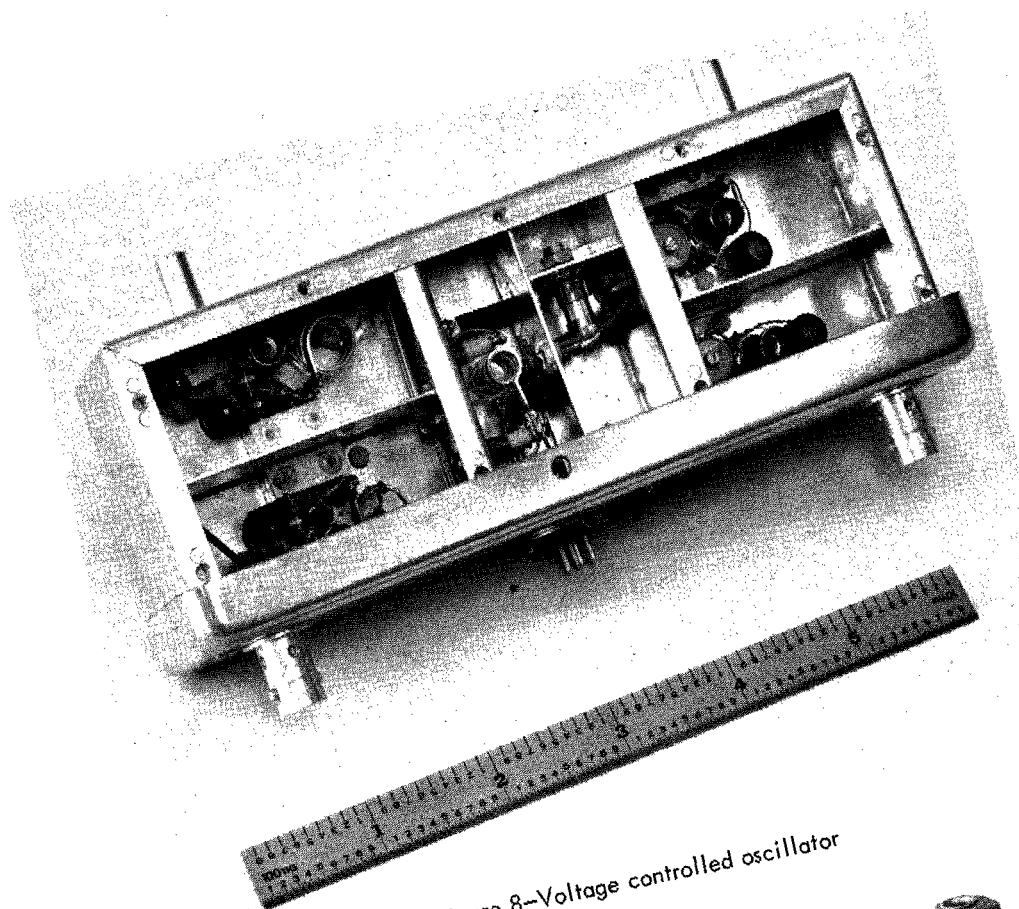


Figure 8—Voltage controlled oscillator

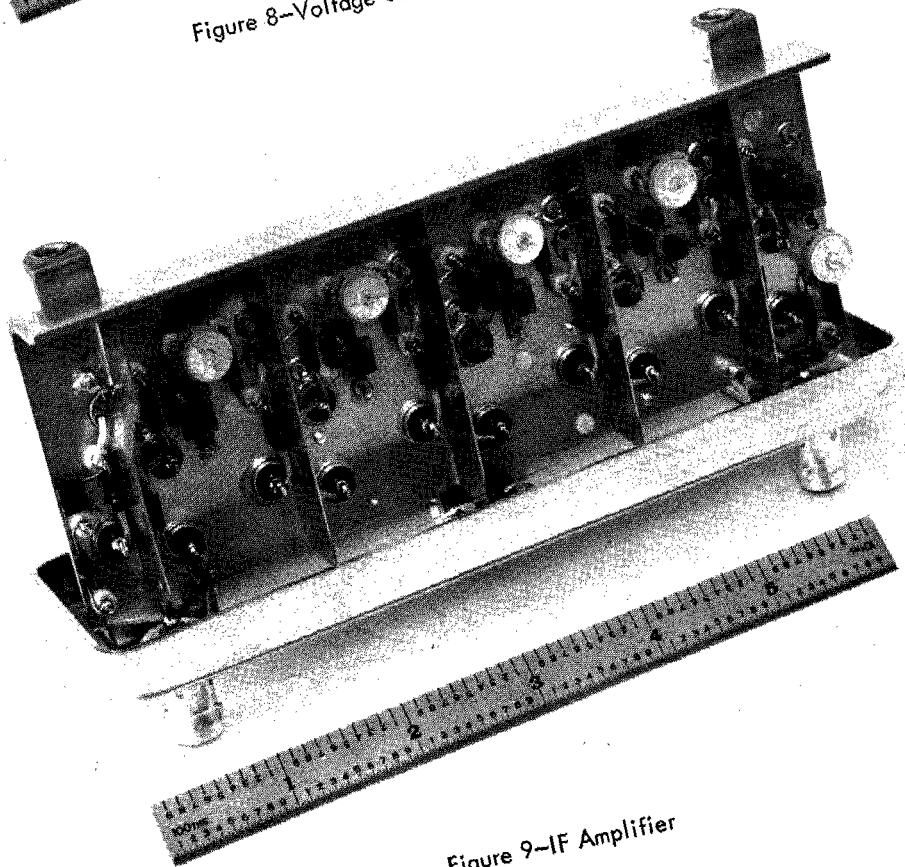


Figure 9—IF Amplifier

EXPERIMENTAL MEASUREMENTS WITH SINUSOIDAL BASE-BAND SIGNAL

Measurements were made to determine the extent to which the performance of the phase-lock demodulator could be predicted by theoretical means. This comparison of experiment and theory should indicate the accuracy to which the loop parameters are known. A simple situation was chosen to simplify the analysis; Figure 10 shows the experimental setup. A sinusoidal base-band signal of 50 kc was used to frequency modulate a 120 Mc IF signal to a peak-to-peak deviation of 20 Mc. Noise was added to this FM signal, and the sum was amplified and applied as the input to the phase-lock demodulator. The noise in a 1 Mc band was measured with a low pass filter and a true rms meter. The signal component was measured with a harmonic analyzer of 6 cps bandwidth. The experimental results are shown by the circles in Figure 11.

A quasilinear analysis* has been applied† for an approximate evaluation of the expected signal-to-noise ratio in the output of the phase-lock demodulator; this analysis can be applied down to an input signal-to-noise ratio of approximately 0 db. The quasilinear analysis indicates that this value of input should correspond to a threshold in some sense. The analysis is not applicable below this point, but the output signal-to-noise ratio should decrease rapidly—as it does experimentally. For comparison, Figure 11 also shows the expected signal-to-noise ratio output from a standard discriminator with an input identical to that of the phase-lock demodulator.

EXPERIMENTAL TV DATA

The present phase-lock demodulator was designed principally for the demodulation of TV signals. Extensive measurements have been performed to determine the IF signal-to-noise ratio required to

*Boonton, R. C., Jr., "The Analysis of Nonlinear Control Systems with Random Inputs," in *Proc. of the Symposium on Nonlinear Circuit Analysis*, Polytechnic Institute of Brooklyn, 23-24 April 1953, p. 369-391.

†Application of the quasilinear analysis to the phase-lock loop was suggested and performed by J. A. Develet, Jr.

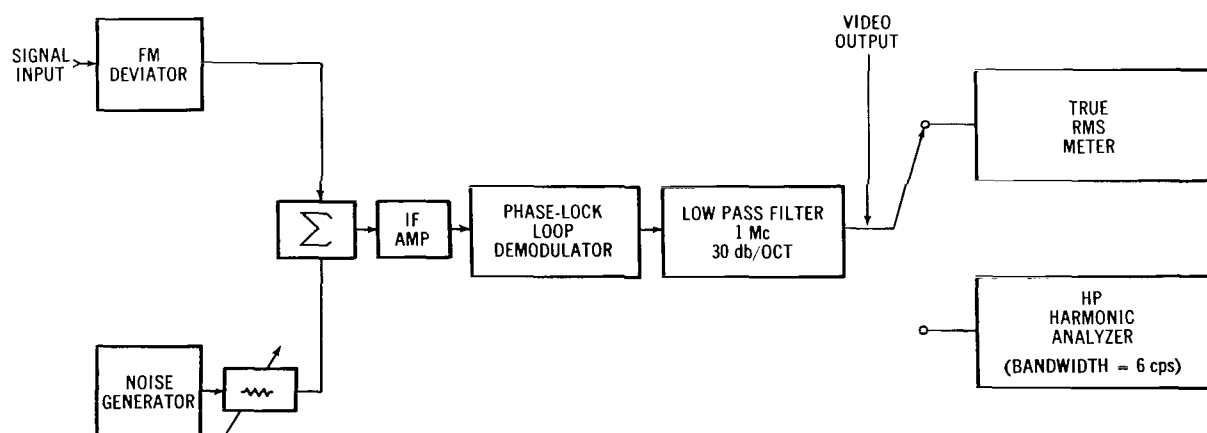


Figure 10—Experimental setup for sinusoidal signal measurement

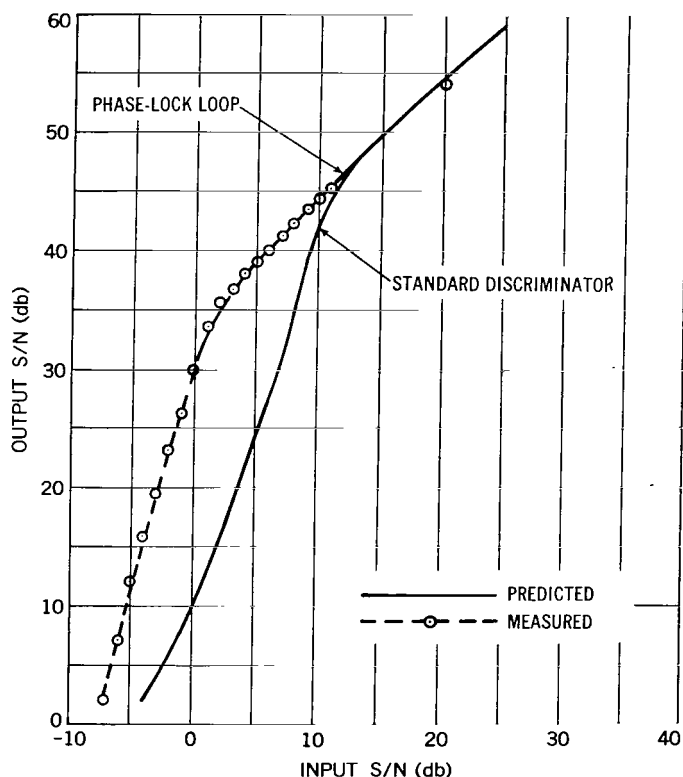


Figure 11—Experimental measurement of signal-to-noise ratio

a phase-lock demodulator and a conventional discriminator, each of which is used to control a monitor. The quantity of direct interest is the IF signal-to-noise ratio required to give satisfactory performance.

Figure 13(a) compares the output of the two monitors when no noise is added to the signal. Figure 13(b) compares the two monitor pictures with a 12-db IF signal-to-noise ratio (S/N) and illustrates that at high signal-to-noise ratios the performance of the phase-lock demodulator and the standard

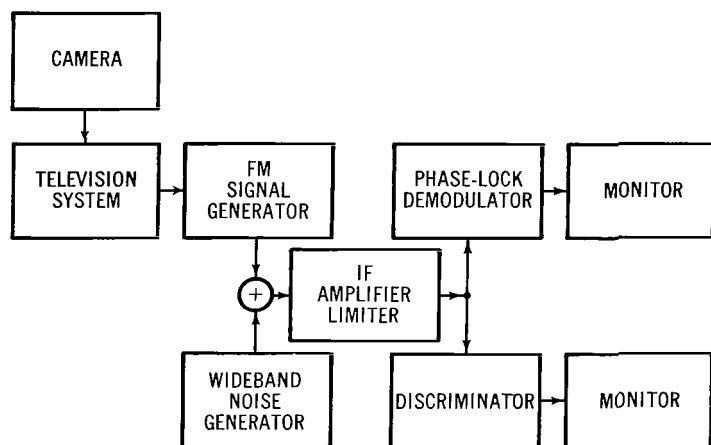
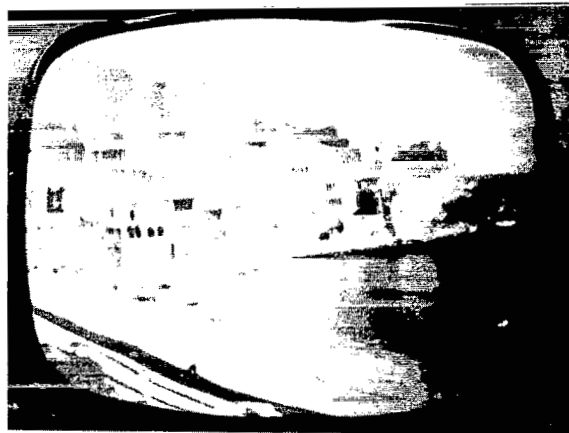
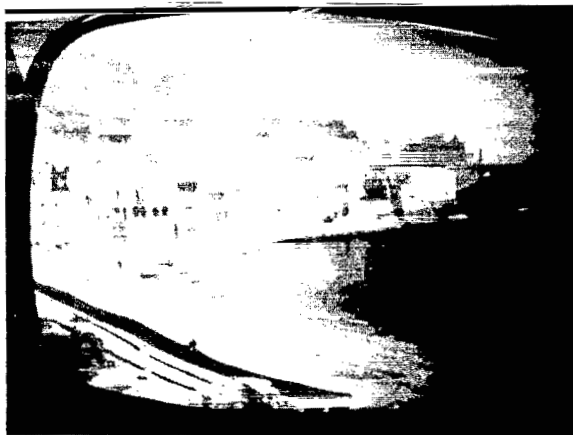


Figure 12—Experimental setup for TV measurements

give satisfactory picture quality. As a reference point, the output of the phase-lock demodulator is compared with the output of a conventional FM discriminator. Figure 12 shows the experimental setup for such a comparison. A closed-circuit camera, together with the associated television circuitry, derives a video signal used to frequency modulate a carrier at the normal IF frequency of 120 Mc. Standard program material transmitted by a Los Angeles TV station has also been used. Carefully shaped and measured wide-band noise is added to the frequency-modulated signal, and the sum is amplified and limited at the IF frequency. The noise bandwidth is the minimum bandwidth capable of satisfactorily transmitting the signal. The output of the IF amplifier limiter is an accurate simulation of the signal plus noise that would appear at the input to the demodulator in a communication satellite experiment. This simulated IF signal is used to drive in parallel

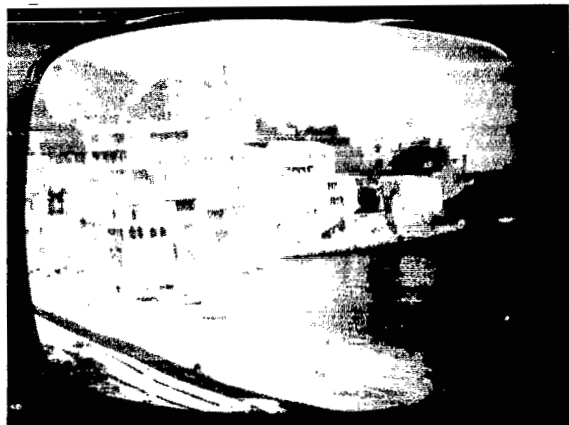
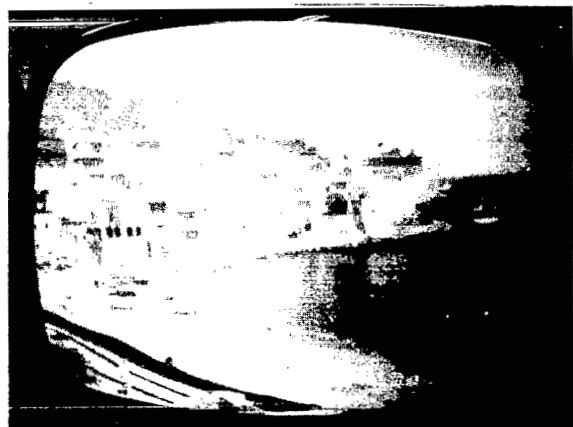
a phase-lock demodulator and a standard discriminator. In Figures 13(c) through (i) the two monitor pictures are shown with S/N = 8 db, 4 db, 2 db, 0 db, -1 db, -2 db, and -3 db respectively. As the signal-to-noise ratio is decreased, both monitors indicate a steadily worse picture quality with this important difference: The standard discriminator output degrades more rapidly than the phase-lock demodulator output. Figure 13(c), for example, illustrates the situation for S/N = 8 db, which is just below the threshold of 10 to 12 db commonly assumed for a standard discriminator. The discriminator output



(a) WITH NO NOISE

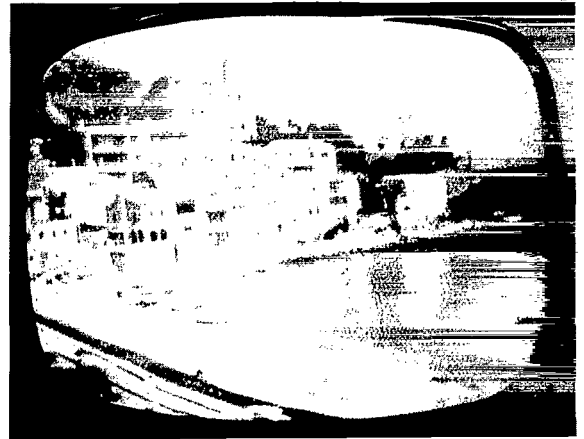
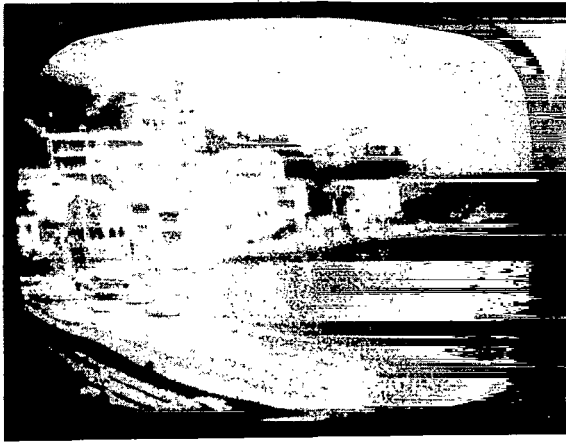


(b) $S/N = 12 \text{ db}$

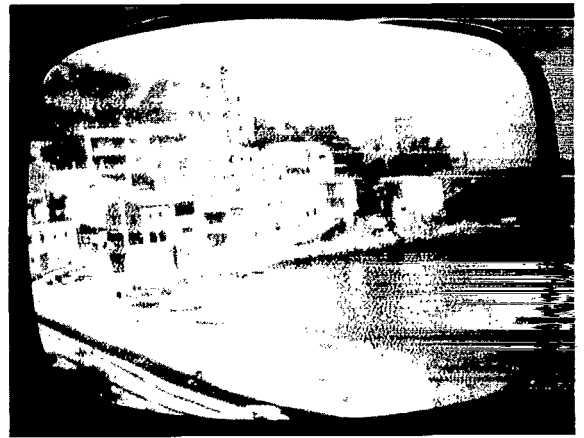
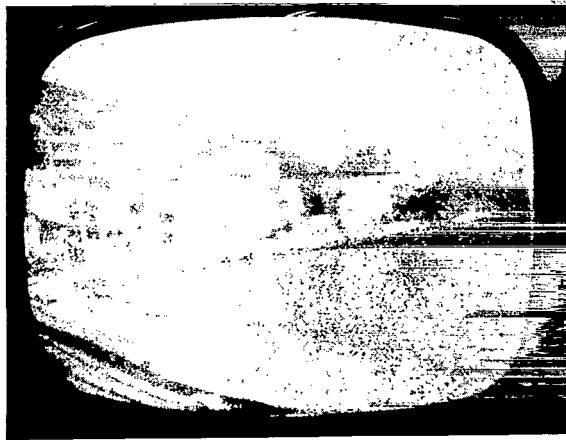


(c) $S/N = 8 \text{ db}$

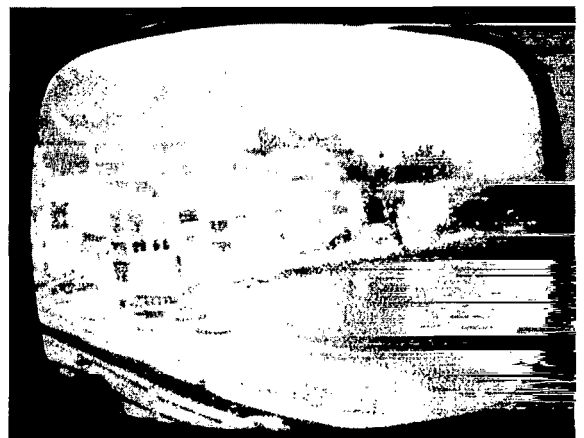
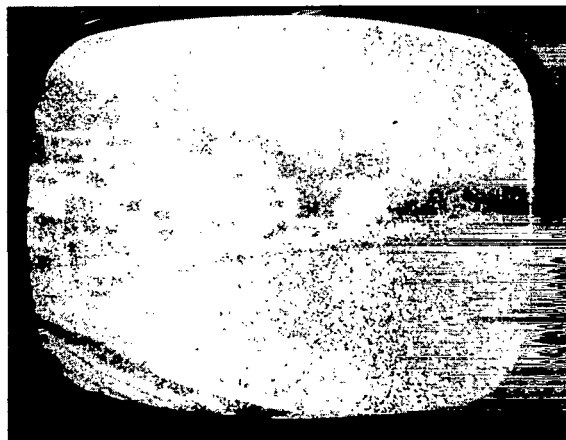
Figure 13—Monitor pictures with a conventional discriminator (left-hand view) and a phase-lock demodulator (right-hand view)



(d) $S/N = 4 \text{ db}$

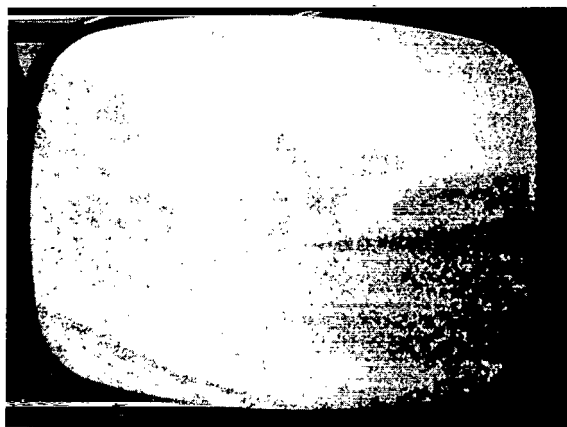


(e) $S/N = 2 \text{ db}$

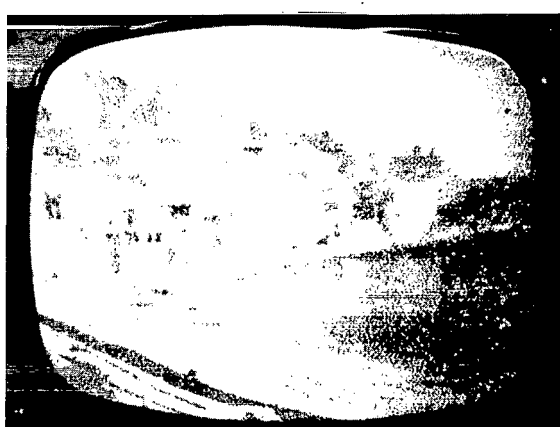


(f) $S/N = 0 \text{ db}$

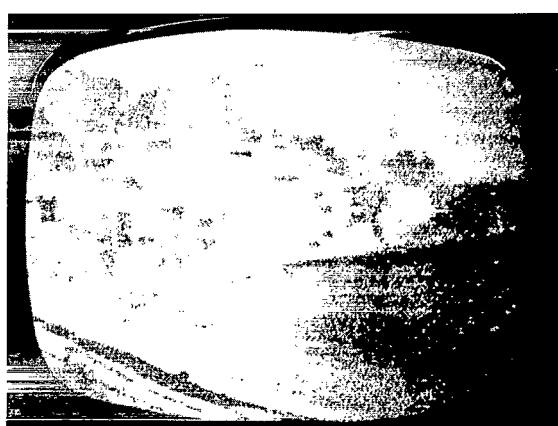
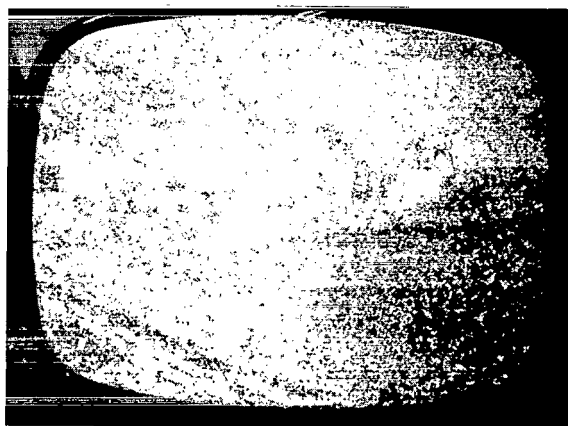
Figure 13 (Continued), -Monitor pictures with a conventional discriminator (left-hand view) and a phase-lock demodulator (right-hand view)



(g) $S/N = -1 \text{ db}$



(h) $S/N = -2 \text{ db}$



(i) $S/N = -3 \text{ db}$

Figure 13 (Concluded)—Monitor pictures with a conventional discriminator (left-hand view) and a phase-lock demodulator (right-hand view)

is beginning to show the effects of the noise, whereas the phase-lock picture is essentially unaffected by the noise. Comparison of the monitor pictures for the two demodulators involves a subjective comparison because of the somewhat different nature of the noise on the picture (described below). Most observers seem to agree, however, that threshold conditions for the two demodulators occur with the standard discriminator requiring approximately 5 db more signal-to-noise ratio; for example, the phase-lock monitor output for the -1 db signal-to-noise ratio has approximately the same picture quality as the standard discriminator output with a signal-to-noise ratio of +4 db.

The noise output of the standard discriminator gives a picture of uniform grain. The principal effect of noise on the phase-lock demodulator, however, is strikingly different. At random intervals the phase-lock demodulator will lose lock. After loss of lock the base-band output tends to go to full black or full white for a very short interval. After this short interval the demodulator locks up again. The losses thus appear in the monitor picture as short black and white horizontal lines.

CONCLUSIONS

The design effort discussed in this paper was directed toward the development of a discriminator that (1) could be used with a high deviation frequency-modulated signal with a base-band signal consisting of a 525 line video plus a 4.5 Mc aural subcarrier, and (2) would reduce the threshold by approximately 6 db below the threshold of a standard discriminator. The principal design problem overcome during the development was the decrease of the loop time delay sufficiently that a loop bandwidth of approximately 7.5 Mc could be achieved without stability problems. This problem was solved satisfactorily by reduction of the unit time delays to the point where the total time delay is less than 30 nanoseconds. Although extensive measurements have been made to verify the dynamic properties of the loop, perhaps the best illustration that the development was satisfactory lies in the quality of the monitor pictures shown in this paper.

ACKNOWLEDGMENTS

The support and encouragement of the Goddard Space Flight Center, specifically D. G. Mazur and R. J. Mackey, are gratefully acknowledged. Special appreciation is due the members of the STL Communication Laboratory, in particular J. A. Develet, Jr., C. W. Stephens, K. H. Hurlbut, and W. A. Garber, for the development described in this paper.

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